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## Herwig++ 2.6 Release Note

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### Abstract

A new release of the Monte Carlo event generator **Herwig++** (version 2.6) is now available. This version comes with a number of improvements including: a new structure for the implementation of next-to-leading order matrix elements; an improved treatment of wide-angle gluon radiation; new hard-coded next-to-leading order matrix elements for deep inelastic scattering and weak vector boson fusion; additional models of physics beyond the Standard Model, including the production of colour sextet particles; a statistical colour reconnection model; automated energy scaling of underlying-event tunes.

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# 1 Introduction

The last major public version (2.5) of `Herwig++`, is described in great detail in [1–4]. This release note describes all changes since version 2.5. The manual will be updated to reflect these changes and this release note is only intended to highlight these new features and the other minor changes made since version 2.5.

Please refer to [1] and the present paper if using version 2.6 of the program.

## 1.1 Availability

The new program version, together with other useful files and information, can be obtained from the following web site:

<http://herwig.hepforge.org/>

In order to improve our response to user queries, all problems and requests for user support should be reported via the bug tracker on our wiki. Requests for an account to submit tickets and modify the wiki should be sent to `herwig@projects.hepforge.org`.

`Herwig++` is released under the GNU General Public License (GPL) version 2 and the MCnet guidelines for the distribution and usage of event generator software in an academic setting, which are distributed together with the source, and can also be obtained from

<http://www.montecarlonet.org/index.php?p=Publications/Guidelines>

# 2 POWHEG

A new simulation of Deep Inelastic Scattering (DIS) and Higgs production via vector boson fusion (VBF) in the PPositive Weight Hard Emission Generator (POWHEG) scheme are included for the first time in this release. The kinematics of these processes are similar, in both cases the momenta of the off-shell vector bosons are preserved. The implementation and physics of these processes is described in more detail in Ref. [5].

The simulation of photon pair production in the POWHEG scheme, described in Ref. [6], is not included in this release as it requires the full framework for the simulation of photon production in the parton shower. This will be available in a future release.

### 3 The Matchbox NLO framework

With version 2.6, a new module for calculating next-to-leading order (NLO) cross sections is provided. **Matchbox** is able to assemble complete NLO calculations, featuring, amongst other required ingredients, an automated dipole subtraction algorithm. These calculations can eventually be matched to showering performed either via a POWHEG-type matching to the standard angular ordered shower and to the newly developed dipole shower described below, or by a MC@NLO-type matching to the dipole shower. First results are presented in [7], and further processes are under development.

**Matchbox** requires an external code to deliver tree-level and one-loop helicity amplitudes dependent on colour structures appearing in the process. Colour structures for simple processes involving vector bosons and up to four partons are already provided, a code dealing with general colour structures will be included in a future version [8]. On top of this interface, connections to external codes can also be performed at the level of matrix elements squared, Born-virtual interferences and colour/spin correlated matrix elements, respectively, or a mixture of amplitude level and cross section level interfaces. More details on **Matchbox** will be the subject of a future publication.

**Matchbox** is able to turn a partonic NLO calculation into process matched to the parton shower in the POWHEG scheme, making use of adaptive methods for sampling Sudakov-type distributions [9]. Full truncated showering for the angular ordered parton shower will be supported in an upcoming version, whereas using the dipole shower algorithm, no truncated showering is required. A set of input files tailored for the simulation of  $e^+e^- \rightarrow q\bar{q}$ , inclusive DIS and inclusive Drell-Yan  $Z$  production at LO and NLO is provided in the release.

### 4 Matrix element merging with **AlpGen**

In order to obtain a realistic simulation of processes involving associated high- $p_T$  jet production, e.g.  $W/Z/\text{Higgs+jets}$ , the parton shower approximation for the generation of soft and collinear QCD radiation must be supplemented by high multiplicity tree-level matrix elements. Matrix element-parton shower merging schemes, such as the so-called MLM and CKKW [10–15] methods, have been developed for this purpose. These methods work by partitioning phase space, by means of a jet algorithm, such that the distribution of jets, so defined, corresponds to that of the partons in the matrix elements, while the distribution of radiation inside the jets is appropriately developed by the shower. In addition, both the MLM and CKKW algorithms augment the distribution of radiation in the matrix element region with Sudakov suppression effects, not present in the matrix elements themselves, thus smoothing the transition from one radiation pattern to another at the phase space partition.<sup>1</sup>

Version 2.6 of **Herwig++** includes an implementation of the MLM merging scheme [11,12,16], through an interface to the tree-level matrix element based event generator **AlpGen** [17]. The current version of the merging algorithm has been validated against its **FORTRAN HERWIG** counterpart for inclusive jet production and jet-associated  $W^\pm$ ,  $Z$ ,  $W^\pm W^\mp$ ,  $H$ ,  $W^\pm b\bar{b}$ ,  $t\bar{t}$ ,  $\gamma$ ,  $W^\pm\gamma$  production processes, at the hadron level, with no underlying event simulation, using the **Rivet** analysis framework and **Agile** interface [18]. Many distributions were inspected, the vast majority of which showed remarkable agreement between **Herwig++** and **FORTRAN HERWIG**. Systematic differences were observed in jet mass distributions and in the Sudakov region of the  $p_T$  spectra of the leading order systems, with **Herwig++** having a tendency to produce lower

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<sup>1</sup>For a full, comparative description of the available schemes, see Ref. [16].

mass jets and a slightly narrower Sudakov region. We have examined particularly the latter cases of difference — though the two are surely highly correlated — and have attributed them to the different showering and hadronization mechanisms (and their associated parameters) rather than the matrix element merging algorithm; in particular we find the differences remain when *only* the native **Herwig++** matrix elements are used and the program is run in its default mode, *i.e.* without any matrix element merging modules.

The code required to perform matrix element-parton shower merging comprises of a stand-alone program to convert **AlpGen** event files to the Les Houches format, **AlpGenToLH**, and two dynamically loadable **Herwig++** modules: a Les Houches event file reader, **BasicLesHouchesFileReader**, and **AlpGenHandler**, a derived **ShowerHandler** implementing the MLM merging algorithm. The three elements are compiled by running `make` in the **Contrib** directory and subsequently the **AlpGen** directory therein. The resulting `.so` modules should be copied to the **lib** directory of the **Herwig++** build and / or installation.

The **Herwig++** interface has the same range of functionality in terms of collider processes and, from the user point of view, the same *modus operandi* as that of **FORTRAN HERWIG**. To generate predictions for, say, inclusive  $W^\pm$  production including matrix element corrections for up to  $N$  additional jets, as input one requires  $N + 1$  **AlpGen** unweighted event files, `W+n.unw`, ( $n = 0 - N$ ) generated in the usual way<sup>2</sup> with, in addition, the associated parameter files `W+n_unw.stat` and `W+n.stat`. With these in hand the first step is to generate Les Houches event files and, simultaneously, **Herwig++** input files by running the **AlpGenToLH** conversion program in the same directory as the `W+n.unw`, `W+n.stat` and `W+n_unw.stat` inputs, supplying the file prefix corresponding to a given set on the command line

```
./AlpGenToLH.exe W+n
```

This produces a Les Houches format event file `W+n.lhe` with the appropriate intermediate particle status codes and mother-daughter assignments, together with a consistent **Herwig++** input file `W+n.in` — these two files are the only input needed for **Herwig++**. **Herwig++** may then be run in the usual way,

```
./Herwig++ read W+n.in
./Herwig++ run -N100 W+n.run
```

The user is only required to edit the input file `W+n.in` for the case that  $n = N$  *i.e.* for the processing of the highest multiplicity event file in the sample, changing 0 to 1 on the line

```
set AlpGenHandler:highestMultiplicity 0
```

The essential difference between showering the events in `W+n.lhe` using the conventional **ShowerHandler** and the **AlpGenHandler** is that the latter implements a rejection of events effecting the Sudakov suppression which is absent in the tree level matrix elements. The results produced by showering all such files may be simply added together yielding those which would be obtained for an inclusive sample. Equivalently, one could combine the individual event files output, as desired.

## 5 Dipole shower algorithm

This version of **Herwig++** includes a first implementation of the coherent dipole shower algorithm as described in [7, 19]. A preliminary tune for both leading order and next-to-leading order

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<sup>2</sup>For details on event generation with **AlpGen** please see the manual [17]

matched simulations is included. This implementation provides an alternative shower module, which particularly eases the matching to NLO calculations. Input files for  $e^+e^-$ ,  $ep$ , and  $pp$  collisions are provided along with the possibility to switch on NLO matching performed by the `Matchbox` module in `LEP-Matchbox.in`, `DIS-Matchbox.in` and `LHC-Matchbox.in`, respectively.

## 6 BSM Physics

A number of new physics models have been added.

### 6.1 Sextet Model

A Sextet diquark model has been added based on the general Lagrangian as discussed in [20]

$$\mathcal{L} = (g_{1L}\bar{q}_L^c i\tau_2 q_L + g_{1R}\bar{u}_R^c d_R) \Phi_{1,1/3} + g'_{1R}\bar{d}_R^c \Phi_{1,-2/3} + g''_{1R}\bar{u}_R^c u_R \Phi_{1,4/3} + g_{3L}\bar{q}_L^c i\tau_2 \tau q_L \cdot \Phi_{3,1/3} + g_2\bar{q}_L^c \gamma_\mu d_R V_{2,-1/6}^\mu + g'_2\bar{q}_L^c \gamma_\mu u_R V_{2,5/6}^\mu + h.c., \quad (1)$$

where  $q_L$  is the left-handed quark doublet,  $u_R$  and  $d_R$  are the right-handed quark singlet fields, and  $q^c \equiv C\bar{q}^T$  is the charge conjugate quark field. The subscripts on the scalar,  $\Phi$ , and vector,  $V^\mu$ , fields denote the SM electroweak gauge quantum numbers:  $(SU(2)_L, U(1)_Y)$ . The Lagrangian is assumed to be flavour diagonal to avoid any flavour changing currents arising from the new interactions.

The kinetic and QCD terms in the Lagrangian, take the usual forms and are

$$\mathcal{L}_{\text{QCD}}^{\text{scalar}} = D^\mu \Phi D_\mu \Phi - m^2 \Phi \Phi^\dagger, \quad (2a)$$

for scalar diquarks, where  $\Phi$  is the scalar diquark field and

$$\mathcal{L}_{\text{QCD}}^{\text{vector}} = -\frac{1}{4} (D^\mu V^\nu - D^\nu V^\mu) (D_\mu V_\nu - D_\nu V_\mu) - m^2 V^\mu V_\mu. \quad (2b)$$

An example input file – `LHC-Sextet.in` – is given and the couplings for the model can be modified in `Sextet.model`. Gluons are excluded from the hard process in the model file by the line

```
insert HPConstructor:ExcludedExternal 0 /Herwig/Particles/g
```

as these are considered to be handled by the Shower. More information on the phenomenology of this model can be found in [20].

### 6.2 Models reproducing CDF $t\bar{t}$ asymmetry

The addition of this model has been motivated by the anomalously large, mass-dependent forward-backward asymmetry in  $t\bar{t}$  production, observed at the Tevatron CDF experiment [21]. Explanation of this asymmetry invokes new interactions in the top sector. In this implementation, we have included four types of new interactions which have been shown to reproduce the measured asymmetry (see, e.g. [22, 23]).

- A flavour-changing  $W$ -prime vector boson which couples top quarks to down quarks:

$$\mathcal{L} \supset \bar{t}\gamma^\mu(g_L P_L + g_R P_R)d W'_\mu + h.c., \quad (3)$$

where  $g_{L,R}$  are the left- and right-handed couplings, i.e. those corresponding to the left- and right-handed projection operators  $P_{L,R}$ , respectively.

- An Abelian  $Z$ -prime vector boson which couples top quarks to up quarks:

$$\mathcal{L} \supset g_{Z'}^{(R,L)} \bar{u} \gamma^\mu P_{R,L} t Z'_\mu + h_{Z',i}^{(R,L)} \bar{u}_i \gamma^\mu P_{R,L} u_i Z'_\mu + \text{h.c.} , \quad (4)$$

where  $g_{Z'}^{(R,L)}$  are the right- and left-handed flavour changing couplings respectively, and  $h_i^{(R,L)}$  are flavour-conserving couplings for the  $i^{\text{th}}$  generation.

- An ‘axial’ heavy gluon which couples to  $\bar{q}q$  and  $\bar{t}t$ :

$$\mathcal{L} \supset g_s [\bar{q} T^A \gamma^\mu (g_L^q P_L + g_R^q P_R) q + \bar{t} T^A \gamma^\mu (g_L^t P_L + g_R^t P_R) t] G'_\mu , \quad (5)$$

where  $g_s$  is the QCD strong coupling,  $T^A$  ( $A \in \{1, 8\}$ ) are the  $SU(3)$  generator matrices in the adjoint representation,  $g_{L,R}^q$  are the left- and right-handed couplings to  $q\bar{q}$  (excluding the top quark), and  $g_{L,R}^t$  is the left- and right-handed coupling to  $t\bar{t}$ .

- A model that includes an additional, non-Abelian,  $SU(2)_X$  gauge interaction. For further details see Ref. [24].

The ‘active’ model can be chosen through the `modelselect` interface in the `TTBA.model` file:

```
set Model:modelselect X
```

where  $X$  signifies the model choice (0 for the  $W'$ , 1 for the  $Z'$ , 2 for the axial gluon and 2 for the non-Abelian  $SU(2)_X$  model). The couplings for each model are self-explanatory and can be also modified in `TTBA.model`. An input file for an LHC run is available as `LHC-TTBA.in`. Note that if the axial gluon model is selected, the following line should be commented out:

```
insert /Herwig/NewPhysics/HPConstructor:Excluded 0 /Herwig/Particles/Ag
```

### 6.3 $Z'$ model

This is a simple model, allowing the addition of a single heavy vector boson ( $Z$ -prime) which is neutral under  $U(1)_{\text{e.m.}}$ . The  $Z'$  of this model is flavour-conserving and the corresponding Lagrangian has the form:

$$\mathcal{L} \supset g_{q_i}^{(R,L)} \bar{q}_i \gamma^\mu P_{R,L} q_i Z'_\mu + g_{\ell_i}^{(R,L)} \bar{\ell}_i \gamma^\mu P_{R,L} \ell_i Z'_\mu + \text{h.c.} , \quad (6)$$

where  $g_{q_i}^{(R,L)}$  and  $g_{\ell_i}^{(R,L)}$  are the right- and left-handed couplings to the quarks and leptons of the  $i^{\text{th}}$  generation respectively. The couplings can be modified in `Zprime.model` and an example input file, `LHC-ZP.in`, is provided.

## 7 Statistical colour reconnection

This release of `Herwig++` comes with a new model for non-perturbative colour reconnections [25], which adopts the Metropolis [26] and the Simulated-Annealing algorithm [27]. Multiple parton interactions and colour connections to beam remnants in hadron collisions lead to heavy colour singlets. To improve the description of underlying-event and minimum-bias observables it has proven inevitable to rearrange colour charges at the non-perturbative stage before hadronization. In the present colour reconnection model this is done with a statistical reduction of the colour length  $\lambda \equiv \sum_{i=1}^{N_{\text{cl}}} m_i^2$ , where  $N_{\text{cl}}$  is the number of clusters in an event and  $m_i$  is the invariant mass of cluster  $i$ .

Data from ATLAS [28,29] and CDF [30,31] prefer a moderate amount of colour reconnection. This corresponds to the colour length  $\lambda$  not being totally minimised by the algorithm. Hence the statistical model reproduces the plain colour reconnection model, which was introduced in `Herwig++ 2.5` [32]. That model tries only a few reconnections in a random sequence.

## 8 Wide-Angle Gluon Radiation

An improved treatment of wide-angle gluon radiation, as described in Ref. [33], is now available. The original and new treatments differ in how the two colour lines of a gluon are evolved in the parton shower. Each of the colour lines has a scale  $\tilde{q}$  proportional to the opening angle. We denote the scale of the colour line with the largest opening angle as  $\tilde{q}_f$  and that of the other colour line as  $\tilde{q}_n$ .

In the original treatment the initial scale of the gluon in the parton shower is given by either  $\tilde{q}_f$  or  $\tilde{q}_n$  with a 50-50 probability. The colour factor used for the gluon is equal to that of the whole gluon,  $C_A$ . Each time an emission occurs the new colour lines are attached to one of the two colour lines of the gluon with a 50-50 probability. When both colour lines have a large opening angle this generates the correct radiation pattern. However, when the opening angle of the two colour lines differ, this approach can generate either too much or too little wide-angle radiation on an event-by-event basis, depending on which of the two partners is initially chosen for each gluon.

The new treatment considers each of the two colour lines to radiate quasi-independently, each with half the gluon's colour factor. The initial scale is always chosen to be  $\tilde{q}_f$  in order to ensure that wide-angle radiation is correctly generated. At the beginning of the shower we have the condition  $\tilde{q}_f \geq \tilde{q} \geq \tilde{q}_n$  and therefore set the colour factor to be  $\frac{1}{2}C_A$  and only attach new colour lines of emissions to the colour line with the larger opening angle. Once  $\tilde{q} \leq \tilde{q}_n$  both colour lines can emit and the colour factor is restored to  $C_A$  and radiation is attached to one of the two colour lines with a 50-50 chance.

In addition to the changes to the behaviour of the parton shower, the change in colour line assignment also modifies the hadronization behaviour. In the original treatment wide-angle radiation could be connected to a small-angle colour line, resulting in a wider regions in which hadrons could be produced. The new treatment ensures that this behaviour does not happen.

The new treatment can be enabled by adding

```
cd /Herwig/Shower
set Evolver:ColourEvolutionMethod 1
set PartnerFinder:PartnerMethod 1
set GtoGGSplitFn:SplittingColourMethod 1
```

to the input file.

## 9 Energy extrapolation of underlying-event tunes

To describe underlying-event data at different c.m. energies it turns out to be sufficient to keep all parameters in the multiple parton interaction model fixed except for the minimal transverse momentum for the additional perturbative scatters,  $p_{\perp}^{\min}$ . The variation of  $p_{\perp}^{\min}$  with  $\sqrt{s}$  is given by a power law,

$$p_{\perp}^{\min}(\sqrt{s}) = p_{\perp,0}^{\min} \left( \frac{\sqrt{s}}{E_0} \right)^b, \quad (7)$$

where  $E_0$  is a fixed reference energy; the default value is 7 TeV. The parameters  $p_{\perp,0}^{\min}$  and  $b$  are obtained from a least-squares fit to tune values at 900, 1800 and 7000 GeV.

To avoid underlying-event tunes for particular c.m. energies to be used in combination with other collider energies, Eq. (7) is hard-coded as of this release of **Herwig++**. In the default **Herwig++** repository,  $p_{\perp,0}^{\min}$  and  $b$  correspond to the interfaces **pTmin0** and **Power** of the **MPIHandler** class, respectively.

## 10 Optional sampler implementations

An extended version of the `ExSample` library [9] is provided with this release. Though `ExSample` is primarily designed for the sampling of Sudakov-type densities, it is equally capable of integrating cross sections and producing unweighted events, thus offering an alternative to the `ACDC` sampler. The extended version additionally provides `SamplerBase` objects which perform either flat or `VEGAS`-type adaptive Monte Carlo integrations, provided mainly for cross checks and not for efficient event generation. The corresponding setup is provided as part of the `Matchbox.in` input file.

## 11 Other Changes

A number of other more minor changes have been made. The following changes have been made to improve the physics simulation:

- Rarely occurring numerical instabilities have been fixed in SUSY events and for extremely off-shell  $W$ -bosons originating from top decays.
- Inconsistent Susy Les Houches spectrum files will now generate more verbose warnings before the run.
- The option of changing the calculation of the transverse momentum of a branching from the evolution variable in final-state radiation has been implemented. While formally a sub-leading choice this enables a better description of the thrust distribution in  $e^+e^-$  collisions at small values of the thrust. Currently the default behaviour, where the cut-off masses are used in the calculation, remains the same as previous versions. In the next release we intend to move to using the virtual off-shell masses of the particles produced in the branching in order to improve the description of the thrust distribution.

A number of technical changes have been made:

- Named, optional weights on top of the usual event weight are now fully supported in `ThePEG`; this includes their communication to `HepMC` events as well as their parsing from the extended Les Houches file format drafted at the Les Houches workshop 2009.
- When simulating minimum-bias events using the `MEMinBias` matrix element, the correct unitarized cross section is now reported via the standard facilities; it is no longer necessary to extract it from the `.log` file of the run.
- The build now depends on the `Boost` libraries. They will be autodetected by `configure`. Alternative install locations can be specified using `--with-boost`.
- The `Tests` directory now contains input cards for almost all `Rivet` analyses. A full comparison run can be initiated with `make tests`.
- The namespace for additional particles has been unified to `ThePEG::ParticleID`.

Support for NLO calculations and easy interfacing to external codes have been added to `ThePEG`:

- ThePEG now includes structures to ease implementing NLO calculations as well as for interfacing external matrix element codes through runtime interfaces. Particularly, the newly introduced [MEGroup](#) and accompanying [StdXCombGroup](#), [StdDependentXComb](#) and [SubProcessGroup](#) classes provide the functionality required by subtraction approaches to higher orders. A general interface for cutting on reconstructed jets as required by higher-order calculations is included, along with an implementation of  $k_\perp$ , Cambridge-Aachen and anti- $k_\perp$  jet finding as relevant for NLO calculations. Hard process implementations deriving from [MEBase](#) are no longer limited to the evaluation of PDFs by [PartonExtractor](#) objects, thus allowing for a more flexible and more stable implementation of finite collinear contributions appearing in the context of higher order corrections.
- The generation of phase-space points for the hard subprocess has been made more flexible, particularly to allow generation of incoming parton momenta by the hard matrix element as is typically done by phase-space generators provided with fixed-order codes. Along with this change, generation of the phase-space point does not need to take place in the centre-of-mass system of the incoming partons.
- Various helpers have been added to [MEBase](#) and dependent code along with the improvements described above, including simple functionality required for caching intermediate results.
- [Tree2toNDiagram](#) supports merging of two external legs, yielding a [Tree2toNDiagram](#) object to assist in determining subtraction terms required for a particular process.

The following bugs have been fixed:

- Susy events read in from Les Houches event files are now handled better.
- The remnant decayer could enter an infinite loop in rare configurations. It will now skip the event after 100 retries.

## 12 Summary

`Herwig++` 2.6 is the eighth version of the `Herwig++` program with a complete simulation of hadron-hadron physics and contains a number of important improvements with respect to the previous version. The program has been extensively tested against a large number of observables from LHC, LEP, Tevatron and B factories. All the features needed for realistic studies for hadron-hadron collisions are present and as always, we look forward to feedback and input from users, especially from the Tevatron and LHC experiments.

Our next major milestone is the release of version 3.0, which will be at least as complete as `HERWIG` in all aspects of LHC and linear-collider simulation. Following the release of `Herwig++` 3.0, we expect that support for the `FORTRAN` program will cease.

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